

**MG ISOTOPIC MEASUREMENT OF FIB-ISOLATED PRESOLAR SILICATE GRAINS.** A. N. Nguyen<sup>1,2</sup>, S. Messenger<sup>1</sup>, M. Ito<sup>1</sup>, and Z. Rahman<sup>1,2</sup>. <sup>1</sup>Robert M. Walker Laboratory for Space Science, ARES, NASA JSC, Houston TX 77058, USA, <sup>2</sup>ESCG/Jacobs Technology, Houston, TX 77058, USA (lan-anh.n.nguyen@nasa.gov).

**Introduction:** The majority of presolar oxide and silicate grains are ascribed to origins in low-mass red giant and asymptotic giant branch (AGB) stars based on their O isotopic ratios. However, a minor population of these grains (< 10%) has O isotopic ratios incompatible with these sources. Two principle alternative sources are higher-than-solar metallicity (Z) stars or, more likely, supernovae (SN) [1-3]. These rare (Group 4) grains [3] are characterized by enrichments in <sup>18</sup>O, and typically also enrichments in <sup>17</sup>O. An even rarer subset of grains with extremely large enrichments in <sup>17</sup>O and smaller depletions in <sup>18</sup>O were suggested to come from binary star systems [2]. To establish the origins of these isotopically unusual grains, it is necessary to examine isotopic systems in addition to O.

Presolar silicates offer several elements diagnostic of their stellar sources and nuclear processes, including O, Si, Mg, Fe and Ca. However, the database for minor element isotopic compositions in silicates is seriously lacking. To date only two silicate grains have been analyzed for Mg [4] or Fe [5]. One major complicating factor is their small size (average ~230 nm), which greatly limits the number of measurements that can be performed on any one grain and makes it more difficult to obtain statistically relevant data. This problem is compounded because the grains are identified among isotopically solar silicates, which contribute a diluting signal in isotopic measurements [1]. Thus, relatively small isotopic anomalies are missed due to this dilution effect. By applying focused ion beam (FIB) milling, we obtain undiluted Mg isotopic ratios of isolated rare presolar silicate grains to investigate their sources.

**Experimental and Results:** Size-separated matrix grains from the carbonaceous chondrite Acfer 094 were analyzed by raster ion imaging in the NanoSIMS 50L ion probe to identify anomalous silicate grains. A ~1 pA Cs<sup>+</sup> primary ion beam was rastered over 20×20 μm<sup>2</sup> areas and the O and Si isotopes, and <sup>24</sup>Mg/<sup>16</sup>O were simultaneously collected. Five “Group 4” silicate grains and one grain (4\_7) having among the highest <sup>17</sup>O enrichments reported in presolar oxides and silicates were targeted for subsequent Mg isotopic analysis. The grains have irregular shapes, and sizes ranging from ~220-500 nm. Because Mg isotopic measurements require use of an O<sup>-</sup> primary ion beam with poorer spatial resolution than the Cs<sup>+</sup> beam, it is critical to mitigate isotopic dilution. This was achieved by removing the surrounding grains by FIB ion milling. Target grains were first covered with a

protective C or Pt cap and then a fine Ga beam was used to remove neighboring matrix material, leaving a 1-1.5 μm clearance around the grain (Fig. 1). The grains were then analyzed for the Mg isotopes, <sup>27</sup>Al, <sup>28</sup>Si and <sup>30</sup>Si by rastering a 4-6 pA O<sup>-</sup> beam over 8 μm fields of view (Fig. 2). One grain was also measured for <sup>29</sup>Si. The matrix grains served as internal isotopic standards, and terrestrial augite was used to determine the <sup>27</sup>Al/<sup>24</sup>Mg relative sensitivity factor.

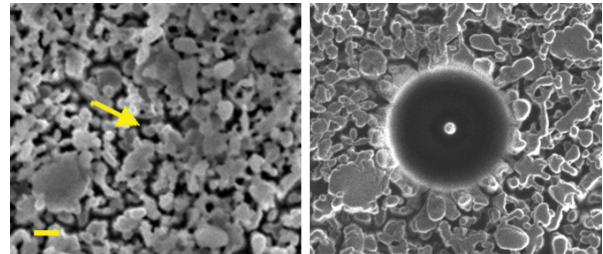


Figure 1. Isolation of a ~240 nm presolar silicate by FIB milling. The scale bar is 500 nm.

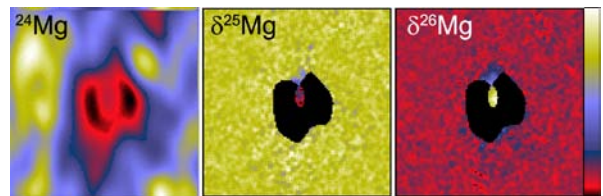


Figure 2. NanoSIMS Mg ion and ratio images of an 8×8 μm<sup>2</sup> region containing a <sup>25</sup>Mg-poor ( $\delta^{25}\text{Mg} = -177 \pm 12\text{‰}$ ) and <sup>26</sup>Mg-rich ( $\delta^{26}\text{Mg} = 357 \pm 15\text{‰}$ ) presolar silicate. Ratios are in delta (δ) notation, or deviations from solar in permil.

**Results and Discussion:** <sup>18</sup>O enriched silicate grains. The O and Mg isotopic compositions of the presolar silicate grains are compared to those of Group 4 presolar oxides of likely SN origin based on multiple isotopic analyses [2,3,6] in Figs. 3 and 4. Two of the five Group 4 silicates have resolvable anomalies in both  $\delta^{25}\text{Mg}$  and  $\delta^{26}\text{Mg}$  and one is enriched in <sup>26</sup>Mg. Mg isotopic compositions indistinguishable from solar were observed for two grains, surprisingly including the one with the second highest enrichment in <sup>18</sup>O ever measured. The Group 4 silicates and oxides tend to have solar or sub-solar <sup>25</sup>Mg/<sup>24</sup>Mg ratios and solar or super-solar <sup>26</sup>Mg/<sup>24</sup>Mg. The Si isotopic compositions of the presolar silicates and those of two SN silicates [5,7] are solar within error. The two SN silicates with the largest <sup>18</sup>O enrichments [8,9] are slightly depleted in <sup>29</sup>Si. Note that the grain identified by [5] was originally declared to have an AGB origin, but later argued by [2] to have condensed in a SN.

Group 4 grains likely come from either high-Z stars

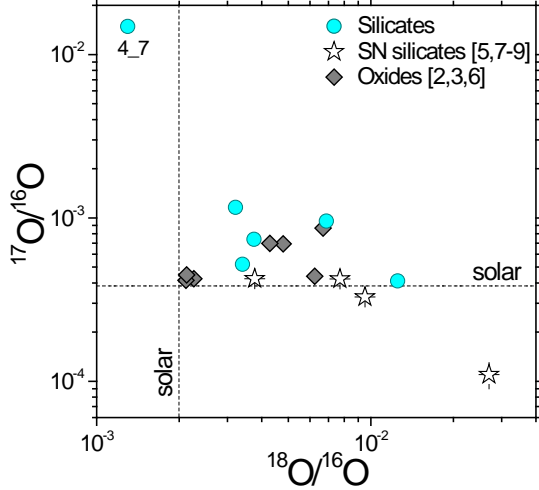


Figure 3. O isotopic ratios of presolar silicates targeted for Mg isotopic analysis compared to those of presolar oxides and silicates of likely SN origin.

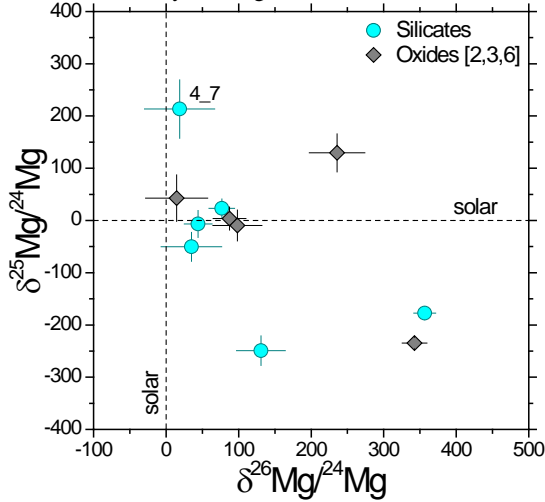


Figure 4. Mg isotopic compositions of presolar silicates from this study and of presolar oxides. Two oxide grains having very large  $\delta^{26}\text{Mg}$  are not shown.

or supernovae. It was recently proposed that most or all Group 4 oxide (and silicate) grains have SN origins, or even condensed in a single SN outflow [2]. High metallicity stars are unlikely sources for any Group 4 grain lacking significant enrichments in  $^{17}\text{O}$ . Moreover, they are unlikely for all the silicates in this study, which do not show the enhancements in  $^{25,26}\text{Mg}$  and  $^{29,30}\text{Si}$  expected from galactic chemical evolution. One grain is slightly  $^{25}\text{Mg}$ - and  $^{26}\text{Mg}$ -rich, but at levels much too low for the metallicity inferred from its O isotopic composition ( $\sim 2Z_{\odot}$ ). Thus, the O, Mg, and Si isotopic compositions of all the Group 4 silicates from this study point to SN sources.

Pre-supernova stars are comprised of concentric zones of distinct chemical and isotopic compositions [10] that undergo extensive mixing during the explosion. As has been done by other authors [2,8], we

mix material from different zones of the Rauscher et al. [11]  $15M_{\odot}$  and  $25M_{\odot}$  solar metallicity SN models to try and reproduce the O, Mg, and Si isotopic compositions of the silicate grains. These three isotopic systems place tight constraints on the mixing details. The isotopic compositions of four grains are well matched by mixing material from 4-5 zones of a  $15M_{\odot}$  SN model. The majority of material comes from the H envelope, He/N and He/C zones, with  $< 1\%$  from the inner zones. The model, however, overproduces  $^{26}\text{Mg}$  in one silicate, and under produces  $^{29}\text{Si}$  in two grains. The latter concern may be resolved in light of a recent report of an unusual SN SiC grain that indicates the  $^{29}\text{Si}$  yield of the O/Ne and O/Si zones should be doubled [12]. Alternatively, the compositions of one of these grains can be matched by a  $25M_{\odot}$  SN. A satisfactory SN mixture for the most  $^{17}\text{O}$ -rich Group 4 silicate has not been identified. Though the O isotopic ratios are matched by He/N zone material, this yields very anomalous Mg isotopic ratios, which are not observed, and  $\text{O/C} < 1$ , which is unfavorable for condensation of O-rich grains.

*Origin of grain 4\_7.* This highly  $^{17}\text{O}$ -enriched silicate grain is slightly  $^{25}\text{Mg}$ -rich and has  $\sim$ solar Si isotopic composition. The large  $^{17}\text{O}$  enrichment of this grain cannot be produced in AGB stars [13]. However, nucleosynthesis models of a  $0.8M_{\odot}$  CO nova match the grain's O and Si isotopic ratios [14]. On the other hand, these models predict much larger  $^{25}\text{Mg}$  enrichments and  $^{26}\text{Al}/^{27}\text{Al}$  ratios than are observed. An alternative explanation is that the parent star of this grain was in a binary system with a nova companion that transferred  $^{17}\text{O}$ -rich matter to the envelope. This type of scenario has been suggested for some oxide grains as well [2].

Clearly, the parent sources of rare presolar silicate populations can be highly constrained by isotopic analysis of multiple elements in single grains, particularly when aided by the novel FIB application described here. From this study it seems plausible that most Group 4 grains come from one SN. Future studies will further investigate the origins of these grains and the importance of binary systems.

**References:** [1] Nguyen A.N. et al. (2007) *ApJ*, 656, 1223. [2] Nittler L.R. et al. (2008) *ApJ*, 682, 1450. [3] Nittler L.R. et al. (1997) *ApJ*, 483, 475. [4] Nguyen A.N. and Zinner E. (2004) *Science*, 303, 1496. [5] Mostefaoui S. and Hoppe P. (2004) *ApJ*, 613, L149. [6] Choi B.-G. et al. (1998) *Science*, 282, 1284. [7] Floss C. and Stadermann F. (2009) *GCA*, 73, 2415. [8] Messenger S. et al. (2005) *Science*, 309, 737. [9] Bland P.A. et al. (2007) *Met. & Planet. Sci.*, 42, 1417. [10] Meyer B.S. et al. (1995) *Meteoritics*, 30, 325. [11] Rauscher T. et al. (2002) *ApJ*, 576, 323. [12] Hoppe P. et al. (2009) *ApJ*, 691, L20. [13] Boothroyd A.I. and Sackmann I.J. (1999) *ApJ*, 510, 232. [14] José J. et al. (2004) *ApJ*, 612, 414.